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Current Transport Mechanisms and Capacitance Characteristic in the InN/InP Schottky Structures

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Abstract: In this work, electrical characterization of the current-voltage and capacitance-voltage curves for the Metal/InN/InP Schottky structures are investigated. We have studied electrically thin InN films realized by the nitridation of InP (100) substrates using a Glow Discharge Source (GDS) in ultra high vacuum. The I (V) curves have exhibited anomalous two-step (kink) forward bias behaviour; a suitable fit was only obtained by using a model of two discrete diodes in parallel. Thus, we have calculated, using I(V) and C(V) curves of Hg/InN/InP Schottky structures, the ideality factor n, the saturation current I_s, the barrier height ϕ_B, the series resistance R_s, the doping concentration N_d and the diffusion voltage V_d. We have also presented the band diagram of this heterojunction which indicates the presence of a channel formed by holes at the interface InN/InP which explain by the presence of two-dimensional electron gas (2-DEG) and this was noticed in the presentation of characteristics C(V). *Copyright © 2014 IFSA.*

Keywords: Indium nitride, Indium phosphide (100), Electrical measurements, Schottky diode.

1. Introduction

In the last few years nitride-based nanostructures have been successfully used in the fabrication of optoelectronic devices as well as in the development of high frequency and high temperature electronic devices. Recent advances in III-nitride deposition techniques have facilitated the growth of high quality InN films and established an updated band gap value of 0.67–0.8 eV [1, 2]. This smaller band gap value has opened the InN/InP structure to electronic and optoelectronic applications.

Our work consists to determining the different electrical parameters of Hg/InN/InP structures using electrical characterization methods (current-voltage, capacitance-voltage). From the forward bias current–voltage (I–V) characteristics, we have determined the saturation current (I_s), ideality factor (n), Schottky barrier height (ϕ_B) and series resistance (R_s). Capacitance–voltage (C–V) measurements also have given detailed information about Schottky contacts. Some parameters of Schottky diode such as barrier height, doping concentration and diffusion potential can be derived from C^{-2} (V) relationship [3, 4]. The measurement of current is used with a measuring instrument "HP 4155 B, Semiconductor Parameter Analyzer" and the measurement of capacitance is used with measuring instrument "Keithley Test System" at high frequency 1 MHz.

We also represented the band diagram of the InN/InP structures which have enabled us to understand the phenomena of transport in these diodes.

2. Technological Part

The substrates of indium phosphide have a circular form of 400 µm thickness and a diameter from approximately 50 mm. These substrates were carried out by Czochralski method and are then cut out according to the crystallographic orientation (100). The samples are doped of 'n' type (N_d is of about 10^{16} cm^{-3}) and they are cleaned by bombarding of Ar^+ ions.

The nitriding of the InP samples is carried out by the source of the plasma type to discharge (glow discharge source (GDS)) to create one or two monolayers of InN on InP(100) substrates through the consumption of indium droplets by nitrogen. We have used the nitrogen flow (grazing flow) versus the normal of the surface during 30 min (sample A) and 40 min (sample B). Low temperature processing is essential in nitriding of InP. The pressure in the deposit room is about 10^{-1} Pa and the samples are heated at 270°C during the nitriding operation. The experimental nitriding conditions have been optimized in others works [5, 6].

3. Results and Discussion

We presented in this part the experimental characteristics I(V) and C(V) of the Hg/InN/InP Schottky structures to extract the different electrical parameters.

The I(V) and C(V) measurements are taken at the room temperature and in the dark. The structures studied are tested electrically with a mercury probe used as a temporary gate contact (see Fig. 1).

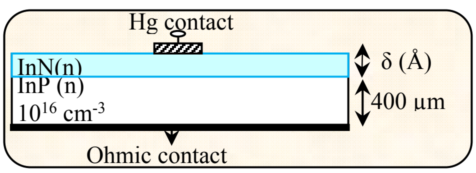

Fig. 1. Schematic of Hg/InN/InP structure.

3.1. Current-Voltage Characteristic

When a Schottky contact with series resistance is considered, it is assumed that the net current of the device is due to the thermionic emission and it can be expressed as [7]:

$$I = I_s\left(\exp\left(\frac{q(V - R_s I)}{nkT}\right) - 1\right), \qquad (1)$$

where V is the applied voltage, R_s is the series resistance, n is the ideality factor and the saturation current I_s is expressed as:

$$I_s = S\,A^* T^2 \exp\left(-\frac{q\phi_B}{kT}\right), \qquad (2)$$

where A^* is the effective Richardson constant (8.76 A cm^{-2} K^{-2} based on the electron effective mass m_e/m_o=0.073 [8] for the InP substrate), S is the area of Hg contact (7.85×10^{-3} cm^2) and ϕ_B is the barrier Schottky.

Fig. 2 shows the Ln(I) versus bias voltage of the study samples. The curves of A and B samples exhibited anomalous Ln(I)-V behaviour which was already observed by S. Ferrero and al. [9] and explained in terms of the presence of two surface phases each having different barrier heights and area.

One diode (D1) represents the bulk barrier height ϕ_B (0 V≤V≤1.1 V) and the other diode (D2) represents a defect region with a barrier height ϕ'_B (V>1.1 V). This behaviour can be explained by the presence a different phenomena, such as barrier inhomogeneities at the metal/semiconductor interface, or presence of defects. We have given in the table 1 only the calculated electrical parameters of the diodes (D1) of samples A and B.

Starting from the first linear region of this curve, we can determine the ideality factor and the saturation current (see table 1). Therefore, we can deduce from relation (2) the barrier height ϕ_B (see table 1). The last linear region shows us the effect of series resistance.

We observed that the ideality factor n and saturation current I_s are better for the sample obtained with nitriding times equal to 40 minutes (sample B) compared to the sample obtained with nitriding times equal to 30 minutes (sample A). The Hg/InN/n-InP Schottky diode with the ideality factor value of 2.56 (sample A) and 2.52 (sample B), which is significantly larger than that for the conventional Au/n-InP Schottky diode obeys a metal–interfacial layer–semiconductor (MIS) configuration rather than an ideal Schottky diode. In other words, the presented I(V) data show a behavior which deviates from pure thermionic emission with n values greater than unity although the structures have behaved like a rectifier contact.

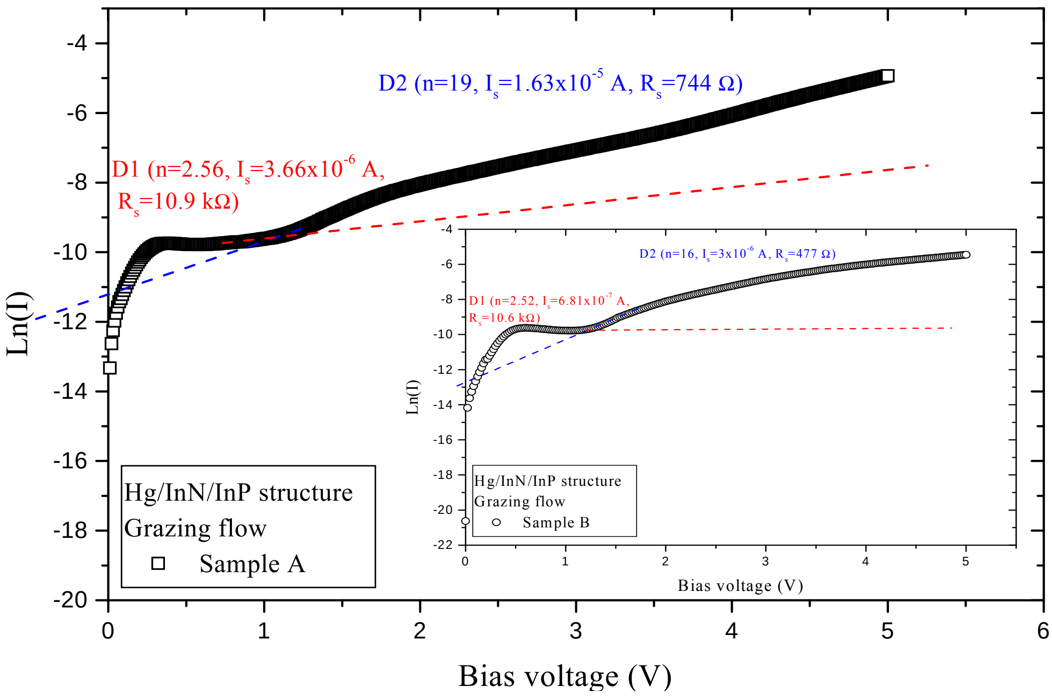

Fig. 2. Experimental I-V characteristic of Hg/InN/InP structure.

Thus the ideality factor is merely a curve fitting parameter to confirm the presence of an interfacial layer consisting of the native oxide plus InN layer between Hg and InP. The studied samples present an important series resistance caused by the InN/InP contacts.

To evaluate the distribution of the interfacial state density N_{ss} in the bandgap of the semiconductor, we used the following expression [10]:

$$N_{ss} = \frac{1}{q}\left[\frac{\varepsilon_i}{\delta}(n-1) - \frac{\varepsilon_s}{W}\right], \quad (3)$$

where ε_i=15.3 ε_0 [2] is the permittivity of the interface layer, ε_s=12.1 ε_0 is the permittivity of InP layer (ε_0=8.85×10^{-12} F/m) and W is the width of the deserted zone calculated from zero bias capacitance C(V) measurement. The thickness of the InN layer δ is equals to 15 Å and 20 Å for the sample A and the sample B, respectively.

In an n-type semiconductor, the energy of the interface states with respect to the bottom of the conduction band at the surface of the semiconductor, E_{ss} is given by [11, 12]:

$$E_c - E_{ss} = q(\phi_B - V, \quad (4)$$

Fig. 3 shows the characteristics of interfacial state density versus (E_c-E_{ss}) of the Hg/InN/InP Schottky structures. The interface state density determined is 8×10^{13} cm^{-2} eV^{-1} and 6×10^{13} cm^{-2} eV^{-1} for the sample A and the sample B, respectively (see table 1).

It can be seen from Fig. 3 that an exponential increase in interface states density exists from mid gap towards the bottom of the conduction band. This rise is less significant for the sample B compared to that of the sample A. At any specific energy, the interface states density of the sample B is lower when compared to that of the sample A.

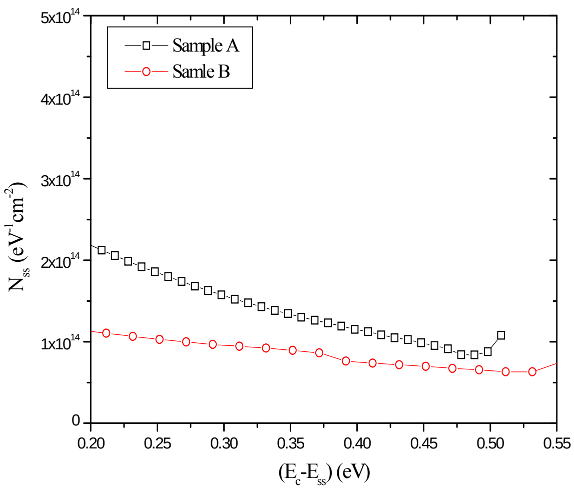

Fig. 3. Variation of the interfacial state density of the studied samples.

The measurements of the capacitance C of the samples are realized at 1MHz. Fig. 4 and Fig. 5 show the C(V) characteristics of the studies structures.

We note that the capacitance variation as a function of the gate voltage shows the existence of a capacitance plateau appearing from 1 V to 4 V, and it is associated to the depletion of the two-dimensional

Table 1. Electrical parameters calculated by I(V) method of the studied samples.

	Sample A	Sample B
Nitriding time (min)	30	40
I_s (A)	3.66×10^{-6}	6.81×10^{-7}
n	2.56	2.52
ϕ_B (eV)	0.54	0.59
N_{ss} (eV^{-1} cm^{-2})	8×10^{13}	6×10^{13}
R_s (kΩ)	10.9	10.6
W (cm) at V=0 V	2.47×10^{-4}	1.08×10^{-4}

Considering the $1/C^2(V)$ curve (see Fig. 4 and Fig. 5), the first linear curve (near V=0 V) is used to evaluate the doping concentration N_d and the diffusion potential V_d of the semiconductor (InP).

The barrier height from C(V) measurement is defined by [4]:

$$\phi_B = V_d - \frac{kT}{q} Ln\left(\frac{N_d}{N_c}\right), \qquad (6)$$

where N_c=0.05×10^{19} cm^{-3} for T=300 K is the effective density of states in InP conduction band.

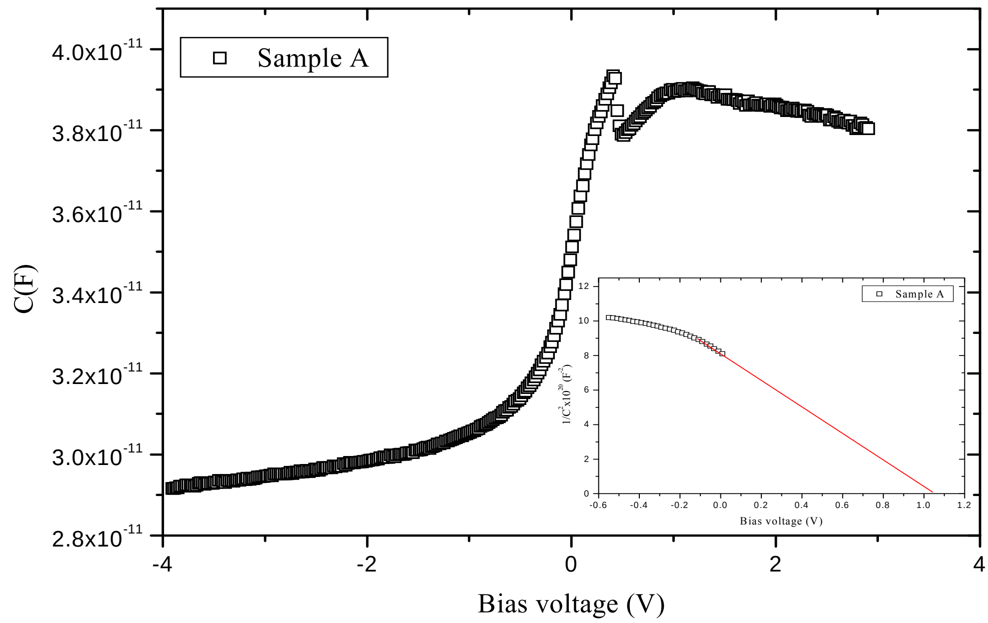

Fig. 4. A plot of C versus V of the sample A.

Between the plateau and the left part, there is a transition region, where the capacitance decreases rapidly with decreasing applied voltage and then increases to 0.4 V from sample A and to 0.9 V from sample B. Then, we observe a sharp fall of the capacitance at the bias voltage 0.38 V for the two samples. The region beyond this voltage is named the residual capacitance region. This is a characteristic of the 2-DEG.

3.2. Capacitance-Voltage Characteristic

The capacitance of a Schottky diode varies with bias voltage as:

$$1/C^2 = \frac{2(V_d - V)}{q\varepsilon_s N_d S^2}, \qquad (5)$$

where N_d is the ionized donor concentration (InP substrate) and V_d is the diffusion potential.

The results of the different measurements are given in the table 2. The doping obtained using calculation is lower compared with the InP concentration. This reduction could be due to the traps associated with the InN film on the surface (is not intentionally doped). The barrier height deduced from C(V) curve is higher than that found by I(V) curve, this is due to the defects on the surface.

Table 2. Electrical parameters calculated by C(V) method of the studied samples.

	Sample A	Sample B
N_d (cm^{-3})	2.57×10^{14}	8.8×10^{14}
V_d (Volt)	1.03	0.75
ϕ_B (eV)	1.2	0.9

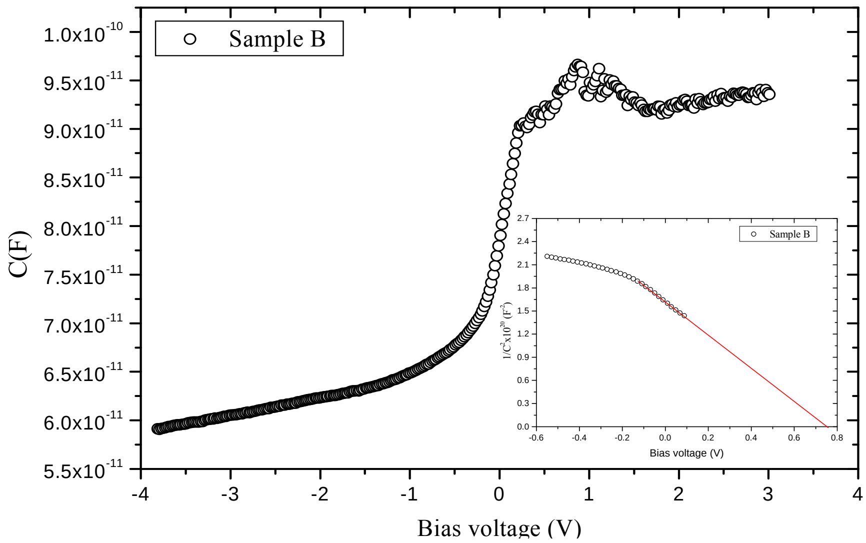

Fig. 5. A plot of C versus V of the sample B.

3.3. Band Diagram

In Fig. 6, we have presented energy band diagram of the InN(n-sc_1)/InP(n-sc_2) isotope heterojuntion at equilibrium (the InN layer is not intentionally doped).

However, the space charge is then an accumulation charge in the InN and a depletion charge in the InP. Diagram showing the presence of a channel formed by holes at the interface (Fermi level in the band valence side InP) and InN is degenerated to the interface (Fermi level in the band conduction) can explain the presence of two-dimensional electron gas (2-DEG). As the thickness of InN deposited is very low, it is supposed that InN behaves like a metal and all the phenomena occur in InP.

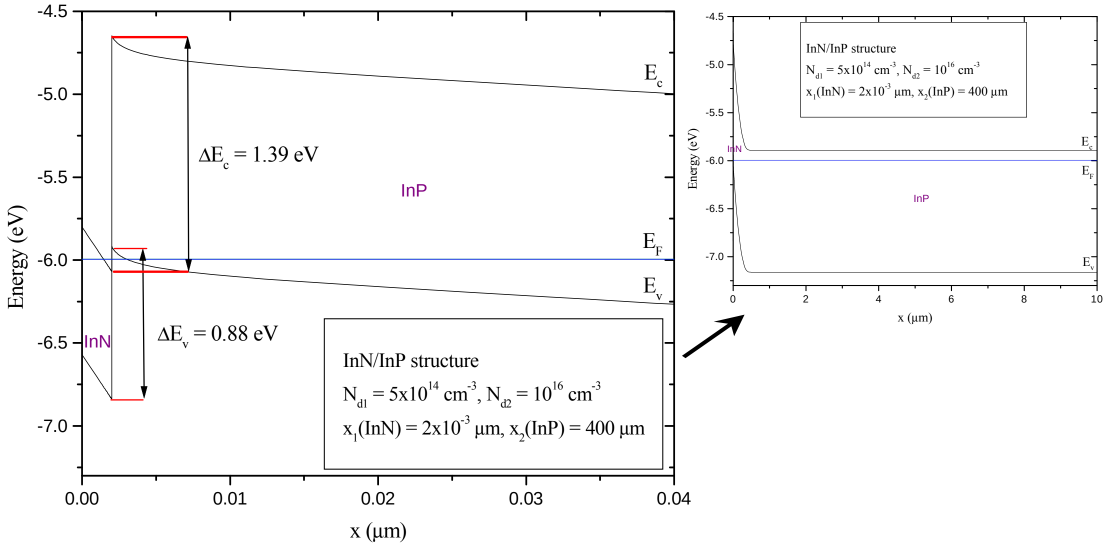

Fig. 6. Energy band diagram of InN(n)/InP(n) structure at equilibrium.

4. Conclusions

We have reported in this paper the results of electrical characterization of Hg/InN/InP Schottky structures. We have demonstrated that the I(V) and

C(V) curves of these heterojunctions are influenced by the presence of the InN layer.

The electrical measurements have demonstrated that the Hg/InN/InP Schottky diode exhibit good rectifying behavior when the nitriding time is about 40 minutes (sample B). There is good agreement among the Schottky diode parameters obtained from the forward bias Ln(I)–V. So, we have determined the ideality factor n = 2.52, the saturation current $I_s = 6.81\times10^{-7}$ A and the height barrier ϕ_B =0.59 eV. The energy distribution of the interface states $N_{ss} = 6\times10^{13}$ eV^{-1} cm^{-2} has been determined from the forward-bias I(V) data. From C(V) curves, we have observed that the defects on the surface induce an additional residual capacity. To decrease the effect of this residual capacity, one proposes to clean chemically the surface in situ well before the deposit of metal

An annealing step at a temperature and a period adequate can also decrease the series resistance and reduce the value of the barrier height determined by C(V) method.

We also showed that the structure presents a two-dimensional electron gas (2-DEG) at the interface InN/InP. Therefore, these structures present good electrical properties.

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